Estuarine Management and Technologies Journal

Estuarine Management and Technologies 1: 69–93 (2024)
DOI: 10.3897/emt.1.137829

Research Article

Delta flood risk analysis: case study from the Neretva River (Croatia)

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Abstract

Floods play an important role in deltas, particularly in their geomorphological and ecological processes. Current deltas are exposed to strong anthropogenic influences. In the Neretva River Delta (Croatia), which is located in the Mediterranean, numerous hydrotechnical facilities have been built for flood protection and flow regulation. The level of flood protection has significantly increased compared to natural conditions, because the main cause of flooding in this delta is fluvial flow, but there are still certain risks for material assets and the population. The hydrological regime of the Neretva River is strongly influenced by reservoirs and hydropower plants built upstream of the basin. This study presents a simulation of floods in the Neretva River Delta for various return periods (from 5 to 1000 years) to assess damages and risks. The extent of flooding is classified into three statistical levels: high, medium, and low probability. Floods in this area can cover approximately 110 km^2 with a low probability of flooding and material damage of approximately 250 million Euros. The average number of potential human victims would be 0.67 per year, and the potential average annual damage would be 11.63 million Euros, in the Donja Neretva according to the conditions of 2015. Climate change would increase the mentioned risks of floods, the potential number of victims and damage by 31 and 41%, respectively. Based on a multi-criteria analysis, protective measures including the construction of embankments and self-regulating gate were proposed. Their implementation would reduce the average annual potential number of victims and the average material damage by 70% and 83%, respectively. The results of this study should be used to identify critical areas and make decisions to improve the flood protection system in the delta area, as well as to improve water management in the entire basin, which is located in the territory of two countries Croatia and Bosnia and Herzegovina.

Key words: Delta, Croatia, flood, Neretva, risk

OPEN ACCESS

Academic editor: Muhammad Wajid Ijaz
Received: 25 September 2024
Accepted: 7 December 2024
Published: 19 December 2024

Citation: Ljubenkov I, Kvesić D, Erceg J (2024) Delta flood risk analysis: case study from the Neretva River (Croatia). Estuarine Management and Technologies 1: 69–93. https://doi.org/10.3897/emt.1.137829

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Introduction

Estuaries and deltas are considered particularly vulnerable to floods. These areas are exposed to water action in two directions. On the one hand, the sea acts on the region (maritime influence), on the other hand, there are meteorological and hydrological processes that occur in the entire basin and affect the natural processes of the estuary and/or delta on the upstream side. Among the mentioned influences, there are several factors (causes) of floods, natural and

human, which often act simultaneously (Bonacci 1987; Kranen 2010; Ljubenkov and Papić 2015; Poulos et al. 2022; Ljubenkov et al. 2024).

Estuaries and deltas are found worldwide in various climatic regions, maritime and continental influences are different and vary over in time (Ward et al. 2018). In general, flood risks are particularly important in low-lying and densely populated estuaries and deltas, where floods can cause human casualties and large material and social damage, as reported in numerous studies (Kranen 2010; Schwarz 2024). In addition to settlements and industrial and commercial facilities, agriculture is often present in these areas. Because of fertile land, large areas along estuaries and deltas were often meliorated, and agricultural production was established in former wetlands globally.

Schwarz (2024) specified the 250 largest deltas in the Mediterranean and provided their basic characteristics, including those of the Neretva River. Most deltas in the Mediterranean are exposed to greater or lesser anthropogenic influences. Hydrotechnical interventions, such as the regulation of watercourses and canals, the construction of infrastructure, or the reduction of flooded areas, lead to changes in space and stop the natural formation of deltas. Schwarz suggested that the protection and restoration of deltas in the Mediterranean should be initiated because these are important ecological systems. Therefore, it is important to analyze extreme situations, such as floods and droughts, because they have a significant impact on the delta region, well as on the natural and social processes that occur there (Meslard et al. 2022).

The Neretva Delta is one of the most valuable wetlands on the eastern coast of the Adriatic Sea and one of the few remaining wetlands in the Mediterranean region of Europe. Although a large part of the former extensive wetlands of the Neretva Delta has been converted into agricultural land, the remaining wetland habitats are representative and important at the international level. Therefore, this delta has been declared a wetland of international importance (Ramsar site) according to the Ramsar Convention of 1992.

In professional literature, estuaries and deltas are often considered from the perspective of small waters. A significant problem affecting deltas and estuaries is the increased intrusion of salt water, which is particularly pronounced during dry conditions (Ljubenkov and Vranješ 2012; Vranješ 2019; Lovrinović et al. 2023; Ljubenkov and Haddout 2024). This leads to an increase in salt content in aquifers and surface waters, which has a direct impact on water supply, agriculture, and other social activities (Romić et al. 2008; Racetin et al. 2020). The processes of salinization during the year are not constant, they vary and depend on hydrological and maritime conditions. The interaction between fresh and saltwater in surface streams and underground is a dynamic process that changes throughout the year. During periods of high water, including floods, the interaction between fresh and saltwater moves downstream and is suppressed by the stronger action of freshwater. Floods and droughts can cause extensive material and social damage and have a strong impact on the ecology. The lack of fresh water in estuaries has been described in numerous studies (Romić et al. 2008; Bellafiore et al. 2021; Kvesić et al. 2024; Ljubenkov and Haddout 2024).

This study focused on fluvial flooding in delta areas. The delta of the Neretva River (Croatia), which flows into the Adriatic Sea in the Mediterranean region, was analyzed in detail. There are eight operational hydropower plants in the

Neretva Basin that directly affect the hydrological regime of the river. However, occasional floods still occur in the downstream of the Neretva River.

Batalla et al. (2004) stated that the magnitude of large waters decreased by 30% on average after the construction of hydropower plants in the Ebro River basin (Spain) compared to the period before their construction. The influence of regulatory and hydrotechnical structures on the hydrological regimes of estuaries has been reported in numerous studies (Bonacci 1987; Kresic 2013; Ljubenkov 2014; Kamidis et al. 2021; Meslard et al. 2022; Poulos et al. 2022). Van Alphen (2016) described a delta flood protection program in the Netherlands and proposed measures to improve it. One method for flood risk assessment is the application of appropriate hydrodynamic models. Suarez and Rodriguez (2007) used the soil and water assessment tool (SWAT) and HEC RAS models to simulate flood risks in the Aguan River Delta area (Honduras). Pramanik et al. (2009) used MIKE FLOOD model to simulate flood inundation extent in the Mahanadi River Delta (India).

To date, many studies and models have been developed to assess the extent of floods in deltas in the world (Pramanik et al. 2009; Belica et al. 2013; Leauthaud et al. 2013; Dinh et al. 2019; Poulos et al. 2022; Khemiri et al. 2024). A few studies refer to the impact of sea level rise on deltas in the Mediterranean (Alvarado-Aguilar et al. 2012; Sayol and Marcos 2018; Falciano et al. 2023). However, there is lack of studies that assess the fluvial flood events, associated damages and risks in deltas, particularly in the Mediterranean. Therefore, this study makes a contribution to the research and provides new perspectives on delta fluvial flooding. The effort becomes more demanding considering the transboundary character of both the Neretva River delta and its catchment, that makes management and mitigation of flooding a challenging task.

The goal of this study was to determine the causes of floods and to quantify large water bodies and their distribution in space using the example of a delta from Croatia, which improves our understanding of these processes. In addition, this study provides a methodology for collecting and analyzing input data to make the best possible assessment of flood risks. Hydrodynamic models MIKE 11 and MIKE FLOOD (DHI) were used to simulate the floods. The EU Directive on the assessment and management of flood risks (2007/60/EC) obliges the EU member states to develop flood risk maps. However, in order to obtain reliable flood risk maps, it is important to select proper type of inundation model as well as properly apply the models. Therefore, this study contributes to this task and proposes practical measures to mitigate floods in the Neretva River delta. Floods are important for numerous aspects of social activity and are important considerations for spatial planning. Therefore, this methodology can be applied to similar systems worldwide.

The flood risk in the Neretva delta was determined in the form of the average annual potential number of victims and damage for three scenarios: a) existing conditions (year 2015), b) the impact of climate change, and c) new conditions with the implementation of recommended protection measures.

The main drawback of this study is that the results of the 2015 research were used (Kvesić et al. 2016). From a hydrological point of view, it would be useful to consider more recent data, i.e. to extend the input series after 2013. Since it is a large and complex system, such modelling would require considerable resources and time. Therefore, the extension of the input hydrologic data could

be considered as part of future activities. In certain areas, only a digital model of the terrain was used instead of geodetic measurements, which gives a certain inaccuracy to the topography of the terrain. Regardless of the stated limitations of the input data, the conducted research determined the critical areas in the Neretva River delta, and the potential damages and risks were quantified.

Study area

The Neretva River rises southeast of the Zelengora Mountain (peak 2032 m above sea level) in Bosnia and Herzegovina (BiH), at a height of 1,095 m above sea level. The total length of this river is approximately 220 km, of which 22 km is in the Republic of Croatia (Fig. 1). The basin of this river, with numerous hydrotechnical structures, is located on the territory of two countries. The management of this system is particularly demanding because it consists of two independent states with separate protocols and professional services. Although the relationships and obligations of both the states regarding water management issues are defined, such systems have certain limitations.

In its upper and middle reaches (upstream from the Počitelj settlement; approximately 35 km from the mouth), the river flows through narrow valleys and canyons, representing a typical mountain river with occasional steep slopes (Fig. 1). After leaving the canyon, the Neretva passes through the valley and has a lowland course with gentle falls.

The total surface area of the Neretva topographic catchment is approximately 10,975 km^2 (Fig. 1) and is mostly spread over the Dinaric Mountain massif in BiH (Bonacci 1987; Bonacci and Jelin 1988; Kresic 2013; Vranješ 2019). Only a small part of the basin (692 km^2) is located in the Republic of Croatia. It is also the most downstream part of the basin, where a complex hydrographic network has developed over an alluvial area of approximately 190 km^2, forming a delta of the Neretva River with numerous branches (Fig. 2) (Ljubenkov and Vranješ 2012; Vranješ 2019; Ljubenkov and Haddout 2024).

The Neretva Delta formed during the last ice age, when the sea level rose and flooded the karst areas along the river to Hutovo Blato. Gravel and sand brought by the river from the upstream part of the basin have been deposited in the valley, thereby increasing the ground level. The delta existed naturally until the end of the 19th century, when the first regulatory work began. This first focused on the maintenance of the waterway from the sea to Metković, for commercial transport. Then, during the 20th century, numerous embankments for flood protection, dams, and other hydrotechnical facilities were built and wetland reclamation began, significantly changing the natural features of the delta. In its current state, downstream from Metković, the river is directed into the main riverbed. In addition to the mainstream, traces of the former delta are visible, including numerous abandoned meanders and backwaters.

In the second half of the 20th century, a number of hydropower facilities with reservoirs were built in the upstream basin of the Neretva, greatly influencing the water regime: hydroelectric power plant (HEPP) Jablanica (1954), HEPP Rama (1969), RHEPP Čapljina (reversible, 1979), HEPP Grabovica (1981), HEPP Salakovac (1981), and HEPP Mostar (1985) (Fig. 1, Table 1). At the beginning of the 21st century, the HEPP Peć Mlini was built on Tihaljina (2004), the right tributary of the Neretva, which is called Trebižat in the downstream, and the HEPP

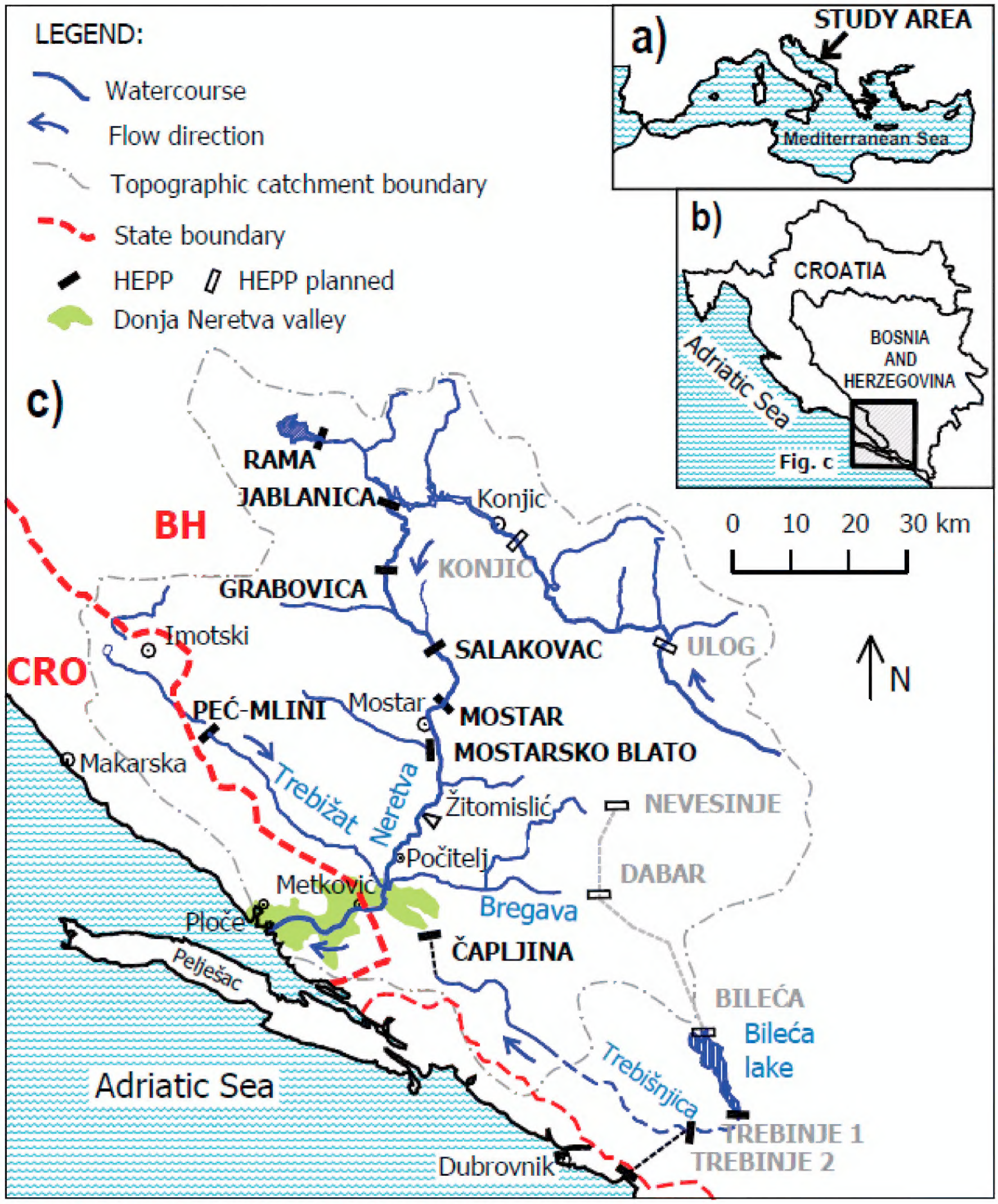

Figure 1. Neretva River basin with marked locations of hydroelectric power plants (HEPP).

Mostarsko Blato (2010). In the upper reaches of the Neretva, the HEPP Konjic was planned, and the construction of the HEPP Ulog began (Fig. 1). In addition to the inflow of the Neretva River, which provides the majority of the water, there are numerous occasional or permanent sources along the edge of the valley (Donja Neretva, Fig. 1) that feed the Neretva and Mala Neretva rivers, particularly during the wet season (Ljubenkov and Vranješ 2012; Ljubenkov and Haddout 2024).

The Neretva and Trebišnjica river basins (Fig. 1) are interconnected through deep and underexplored underground karst. Therefore, it is currently impossible to reliably define their mutual borders, that is, to define their hydrological and hy-

Figure 2. Donja Neretva area with marked locations of meteorological and hydrological stations.

Table 1. Hydroelectric power plants in the Neretva and Trebišnjica river basins.

No.	Name	Year	River	Station of the river (km)	Dam height (m)	Reservoir volume (10^6 m^3)	Installed power (MW)
Neretva River							
1.	Jablanica	1954	Neretva	112	85	318	197
2.	Rama	1969	Rama	-	103	1.45	160
3.	Grabovica	1981	Neretva	95	60	20	117
4.	Salakovac	1981	Neretva	78	70	68	208
5.	Mostar	1987	Neretva	66	28	11	72
6.	Peć Mlini	2004	Tihaljina	44	111	0.8	30
7.	Mostarsko Blato	2010	Neretva	-	-	1.6	60
Trebišnjica River							
1.	Trebinje 1	1968	Trebišnjica	71	123	1277	168
2.	Čapljina	1979	Trebišnjica	0	-	7.2	420
3.	Trebinje 2	1981	Trebišnjica	61	33	16	8

drogeological relationship. The entire area of the Neretva and Trebišnjica basins is represented by developed Dinaric karst, which is characterized by complex surface and underground flow processes (Bonacci et al. 2006; Kresic 2013).

Meteorological and climatological characteristics

The climatological characteristics of the Neretva Basin are characterized by a transition between a moderate continental and maritime regime, given that the largest part of the basin is located in the area of the Dinaric Mountain massif,

which separates the maritime and continental zones. In most of the basin, the most significant precipitation occurs in winter, and the minimum occurs in summer. The average annual precipitation ranges from 1,000 mm on the coast to 1,900 mm in the mountainous parts of the basin. The maximum annual precipitation in the elevated parts of the basin is over 2,900 mm. There are two climatological stations in the Donja Neretva area Metković and Opuzen (Fig. 2, Table 2). Fig. 3 shows the characteristic values of monthly precipitation at Metković station for 2014–2023. On average, the rainiest quarter of the year is November–January, both in the coastal and continental parts of the watershed therefore, it is the period when higher waters in watercourses are most frequent. In this quarter, the highest recorded monthly precipitation was 400 mm (November 2021).

Table 2. Climatological stations in the Donja Neretva (Croatia).

No.	Name	Latitude, Longitude	Elevation (m a.s.l.)	Start of operation (year)
1.	Metković	43°2'47"N, 17°38'35"E	4	1997
2.	Opuzen	43°1'3"N, 17°33'31"E	3	1886

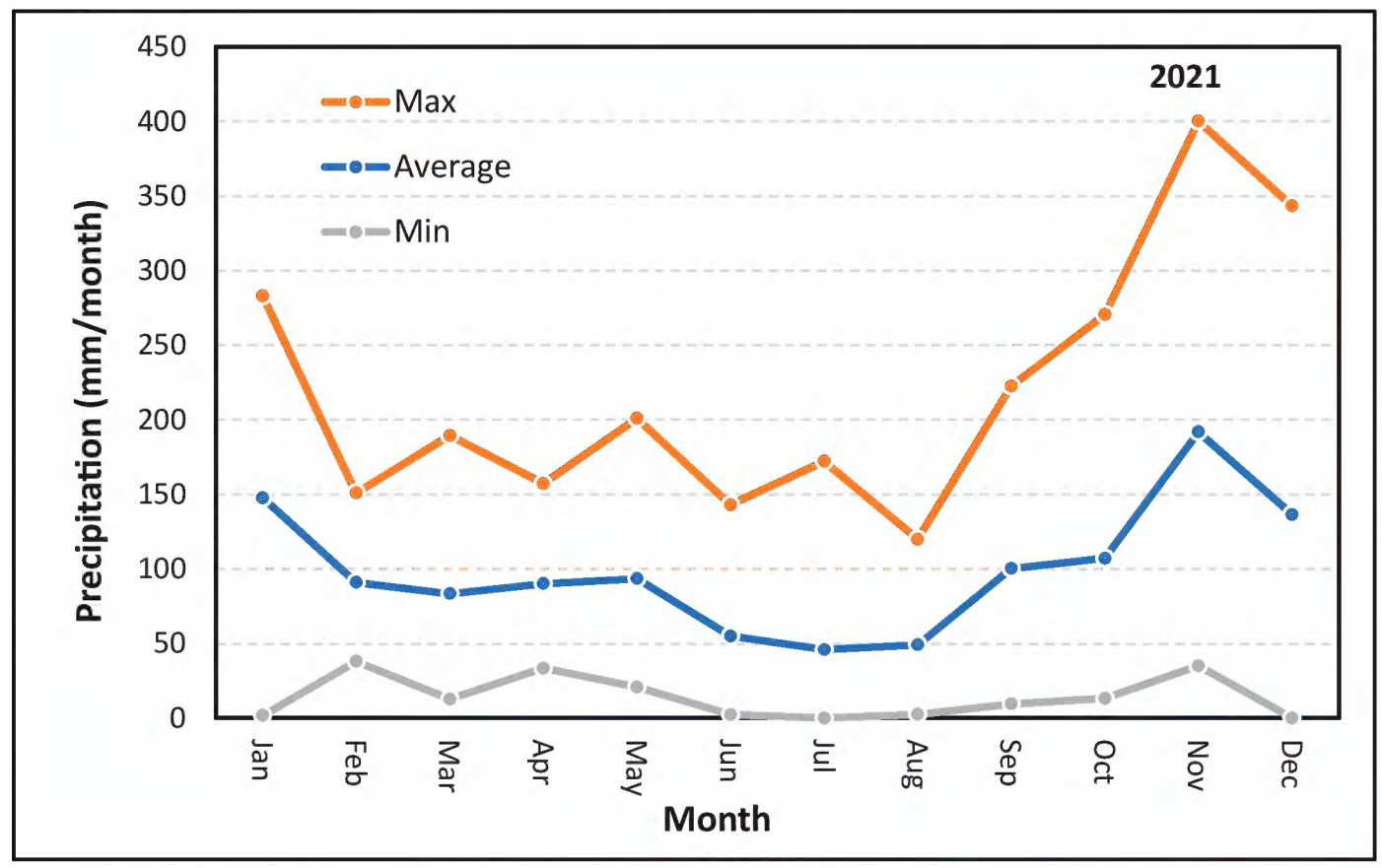

Figure 3. Characteristic values of monthly precipitation (Metković, 2014–2023).

The long-term average air temperature in Donja Neretva ranges from 14 to 16 °C. The highest average monthly temperature occurred in July and the lowest in February. Average daily air temperatures in winter reach -6 °C. The highest mean daily temperatures exceeded 30 °C.

In the Donja Neretva Basin, there are no particularly strong winds, and the dominant winds are *jugo* (southeast wind) and *bura* (northeast wind), which are most common in the spring and November.

Geological structure and hydrological features

In Donja Neretva, the most widespread strata are permeable carbonate deposits, mostly limestone. The basic characteristic is that most of the precipitation water immediately seeps underground, and occasional surface watercourses

are formed only during heavy and long-lasting rains (Bonacci 1987; Bonacci and Jelin 1988; Kresic 2013; Vranješ 2019).

The Quaternary sediments deposited in the valley of the Donja Neretva are fluvial Pleistocene-Holocene sediments composed of porous sandy and clay gravels, which are most often covered with dusty clays whose base is formed by fluvioglacial deposits, because of the high level of underground water. Part of the surface is covered by muddy swampy, and occasionally flooded terrains.

The Croatian Donja Neretva area has twelve operational hydrological stations (Fig. 2). Basic data on the hydrological stations are listed in Table 3. The Metković and Opuzen stations are located on the Neretva River. Water levels are continuously measured at each station. It was not possible to determine the flows unambiguously because of the influence of the sea. Three stations were located on the Mala Neretva watercourse. However, because the inflow into the Mala Neretva is controlled by floodgate, which is lowered during periods of high water, the Mala Neretva accepts only water from its basin. The three hydrological stations are located on the right tributary of the Neretva River, the Norin River. Of these, two are located relatively close to the Neretva (Fig. 2), whereas one is at its source, Prud. Other hydrological stations are located on smaller watercourses of the left tributaries of the Neretva. Two stations are on the Koševo-Vrbovci Lateral canal, one on the Bijeli Vir spring (Mislina River), and one on Lake Kuti.

Table 3. Hydrological stations in the Donja Neretva (Croatia).

No.	Name	River	Start of operation (year)	Station of the river (km)	Level „0" HVRS1875 (m a.s.l.)
1.	Metković	Neretva	1934	21	-0.271
2.	Opuzen Ustava Nizv.	Mala Neretva	1976	10	0.000
3.	Opuzen	Neretva	1887	12	-0.180
4.	Ustava Ušće Uzvodni	Mala Neretva	1977	0	x
5.	Ustava Ušće Nizvodni	Mala Neretva	1976	0	-0.200
6.	Kula Norinska	Norin	1986	0	-0.155
7.	Kalebovac	Norin	1986	3.5	-0.085
8.	Prud	Norin	1953	10	1.319
9.	Bijeli Vir	Bijeli Vir	1960	-	-0.210
10.	Bijeli Vir	Lateral canal	1977	-	-0.023
11.	C.P. Veraja	Lateral canal	1994.	-	0.000
12.	Kuti	Lake Kuti	1953.	-	-0.043

Floods in the Donja Neretva area may have several causes. Floods are primarily caused by the inflow of large waters through the Neretva River from the upstream part of the basin (BiH) and to a lesser extent, by the inflow of water from springs on the right edge of the valley and the rise in sea level due to tides. Floods on the left bank of the Neretva and Mala Neretva rivers are primarily influenced by sources in the Metković-Kuti area (the most significant source is the Bijeli Vir), which are part of the Trebišnjica River basin, the left tributary of the Neretva and the largest European sinkhole river. The smallest impact on the flooding on Neretva was the precipitation that fell directly on the Donja Neretva area. The impact of local precipitation was significant only for floods on the left banks of the Neretva and Mala Neretva rivers. The basin of the Neretva River belongs to the Dinaric Karst. Therefore, most of the precipitation quickly sinks, accumulating

large amounts of water in the underground system, which reappears on the surface via numerous springs, particularly along the edges of the valley, and flows into the Neretva, Mala Neretva, and Norin watercourses. “Stretched” runoff hydrographs are formed under such complex runoff conditions and the interaction of surface and underground water in the Donja Neretva area.

The constructed system of HEPPs, primarily with large storage lakes, such as HEPP Jablanica (Table 1), has a dominant influence on the frequency, extent, and duration of floods in Donja Neretva. In addition, its effect on the flow regime, the construction of reservoirs in the upstream Neretva has a long-term impact on the reduction of sediment delivery to the valley, deepening the Neretva bed. Combined with the reduction in inflow in certain periods, this worsens the problems of water and soil salinity in Donja Neretva.

Water structures constructed on the Trebišnjica River (Table 1) have a dominant influence on the size and duration of floods on the left banks of the Neretva and Mala Neretva rivers. Several of these structures are under construction, and other currently planned, the so-called upper and lower horizons (HEPP Nevesinje, Davar and Bileća; Fig. 1) with the large accumulation lake, Bileća. It will have an area of 33 km^2 and volume of 1,277 mil. m^3, which will further change the hydrological regime of the Trebišnjica River and its influence on Donja Neretva (Vranješ 2019). Floods on the left banks of Neretva and Mala Neretva do not coincide with flood events in Neretva.

The hydrological station furthest upstream on the Neretva River in the Republic of Croatia is Metković, located approximately 21 km from the mouth of the river and 1 km from the state border. This station also represents the upstream boundary conditions of the hydrodynamic model. Fig. 4 depicts a series of maximum and average annual water levels from 1935–2022 (N = 88), with breaks in four years. The highest water levels in Metković (> 430 cm) were recorded in the 1950s before the construction of HEPP Jablanica and HEPP Rama (Fig. 4). After 1961, the highest recorded water level was 414 cm (December 2010) (Table 4). The highest water levels in 2010 caused flooding in a large part of the valley.

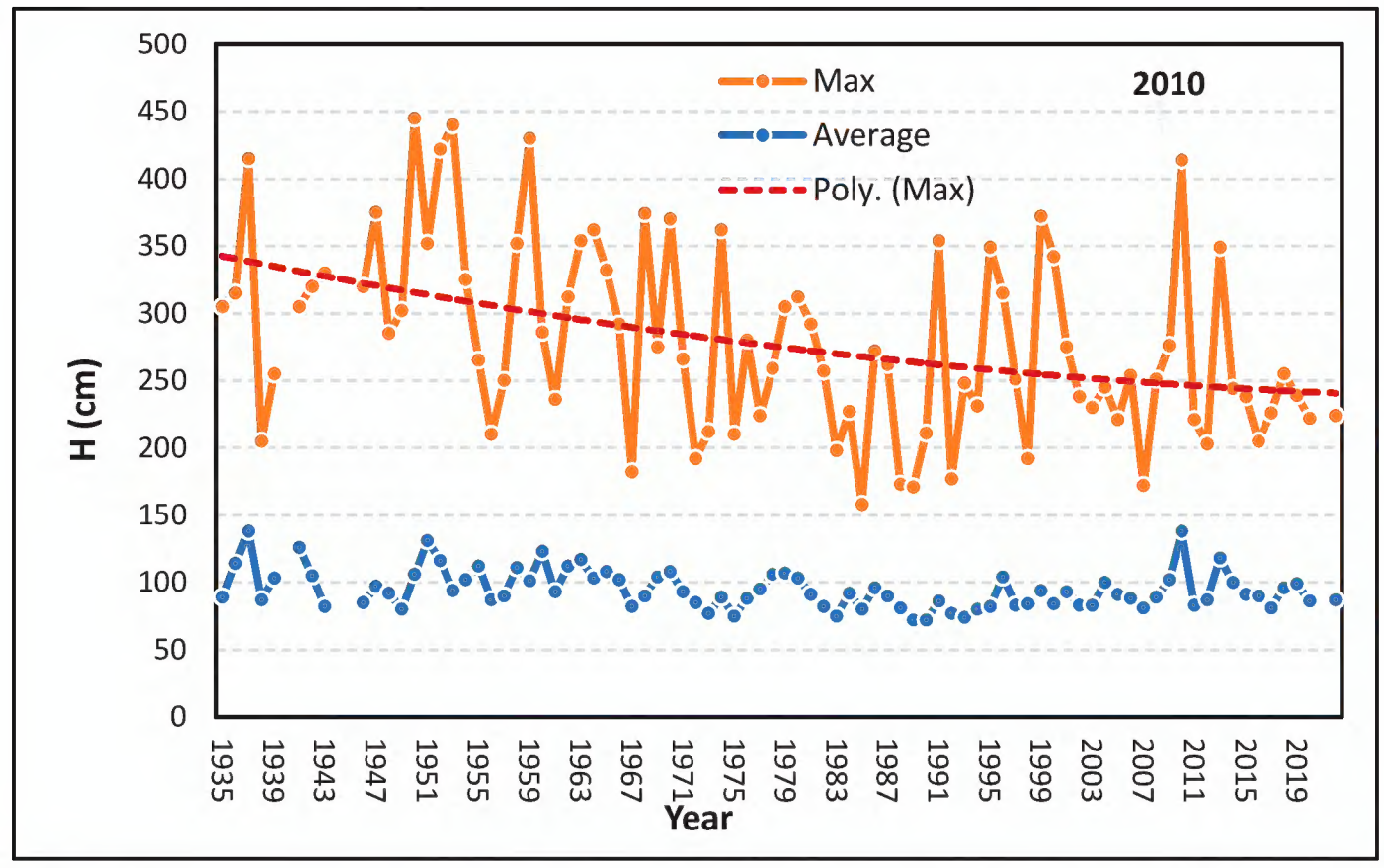

Figure 4. Series of maximum and average annual water levels in Metković (1935–2022).

Table 4. Maximum water levels H (cm) of the Neretva River in Metković.

No.	H (cm)	Date	No.	H (cm)	Date
Period: 1935–2022			Period: 1961–2022		
1.	445	13.12.1950.	1.	414	2.12.2010.
2.	440	2.1.1953.	2.	374	20.12.1968.
3.	430	14.12.1959.	3.	372	17.12.1999.
4.	422	19.12.1952.	4.	370	17.1.1970.
5.	415	17.12.1937.	5.	362	24.10.1974.

High water simulation

Hydrological analysis

The boundary conditions of the model are generally determined by the hydrographic network, the location of the hydrological stations and the available measurements. The state border was used as the upstream edge for simulating floods in the Neretva delta, while the downstream edge was the coast itself. Therefore, hydrological stations Metković and Prud provide upstream boundary conditions, and the Ustava ušće provides downstream boundary condition (Fig. 2). Therefore, the hydrological analysis is focused on these stations.

The assessment of flood risks in the Donja Neretva area is based on data for hydrological measurements of water levels and statistical processing of their series (Kvesić et al. 2016; Mimikou et al. 2016; Ljubenkov et al. 2023; Ljubenkov et al. 2024). The analysis was conducted for the series of available measurements, namely 1961–2013 (N = 53) for Metković, 1977–2013 (N = 37) for the Ustava ušće (sea), and 1978–2013 (N = 36) for Prud. As part of the hydrological analysis, the probability of occurrence of large waters was defined as the result of the statistical analysis of the maximum annual water levels. Furthermore, synthetic water waves were defined as the boundary conditions for the hydrodynamic model of the area considering the large waters of the Neretva River, its tributaries, and the sea coincide.

The probability of large flood occurrence was calculated using five theoretical distribution functions (Gumbel, log-normal, normal, Pearson, and log-Pearson). Based on the analysis of the selected theoretical distribution functions and testing their adaptation to the empirical distribution, the log-normal function for Metković (Table 5), log-Pearson for the sea (Table 6), and log-normal for Prud (Table 7) were selected as the most favorable. The table shows the values of high water content for different return periods based on the selected function.

Table 5. Calculated high waters (Hmax) for different return periods (Metković, log-normal, 1961–2013).

Parameter	Unit of measure	Return period (year)							
		10	20	25	50	100	200	500	1000
Hmax	(cm)	353	386	396	426	455	483	520	548
Hmax	(m a.s.l.)	3.26	3.59	3.69	3.99	4.28	4.56	4.93	5.21

Table 6. Calculated high waters (Hmax) for different return periods (Ustava Ušće Nizvodni, log-Pearson, 1977–2013).

Parameter	Unit of measure	Return period (year)							
		10	20	25	50	100	200	500	1000
Hmax	(cm)	131	138	140	145	150	154	160	163
Hmax	(m a.s.l.)	1.11	1.18	1.20	1.25	1.30	1.34	1.40	1.43

Table 7. Calculated high water (Hmax) for different return periods (Prud, log-normal, 1978–2013).

Parameter	Unit of measure	Return period (year)							
		10	20	25	50	100	200	500	1000
Hmax	(cm)	156	161	162	167	170	174	178	182
Hmax	(m a.s.l.)	2.88	2.93	2.94	2.99	3.02	3.06	3.10	3.14

Hourly water–level measurements were used to define the synthetic–level charts. From the available data, the highest recorded water waves were selected, which were then overlapped with the maximum values (Figs 5–7). Based on the diagrams obtained using the graphical method, synthetic–level charts were created for different return periods in accordance with the calculated maximum. The measurements of larger water waves are also shown in the figures, and the year in which they appeared is indicated. The change in the water level at the Ustava Ušće station represents the marine oscillation (Fig. 6). Tides in the Adriatic Sea have relatively small amplitudes. In the southern Adriatic, this difference rarely exceeds 40 cm, whereas in the northern part, it is approximately 1 m (Fig. 1). During periods of high water, the water level along the entire Norin watercourse is under the slowness of the Neretva, which can be seen in the measurements at the Prud station (Fig. 7).

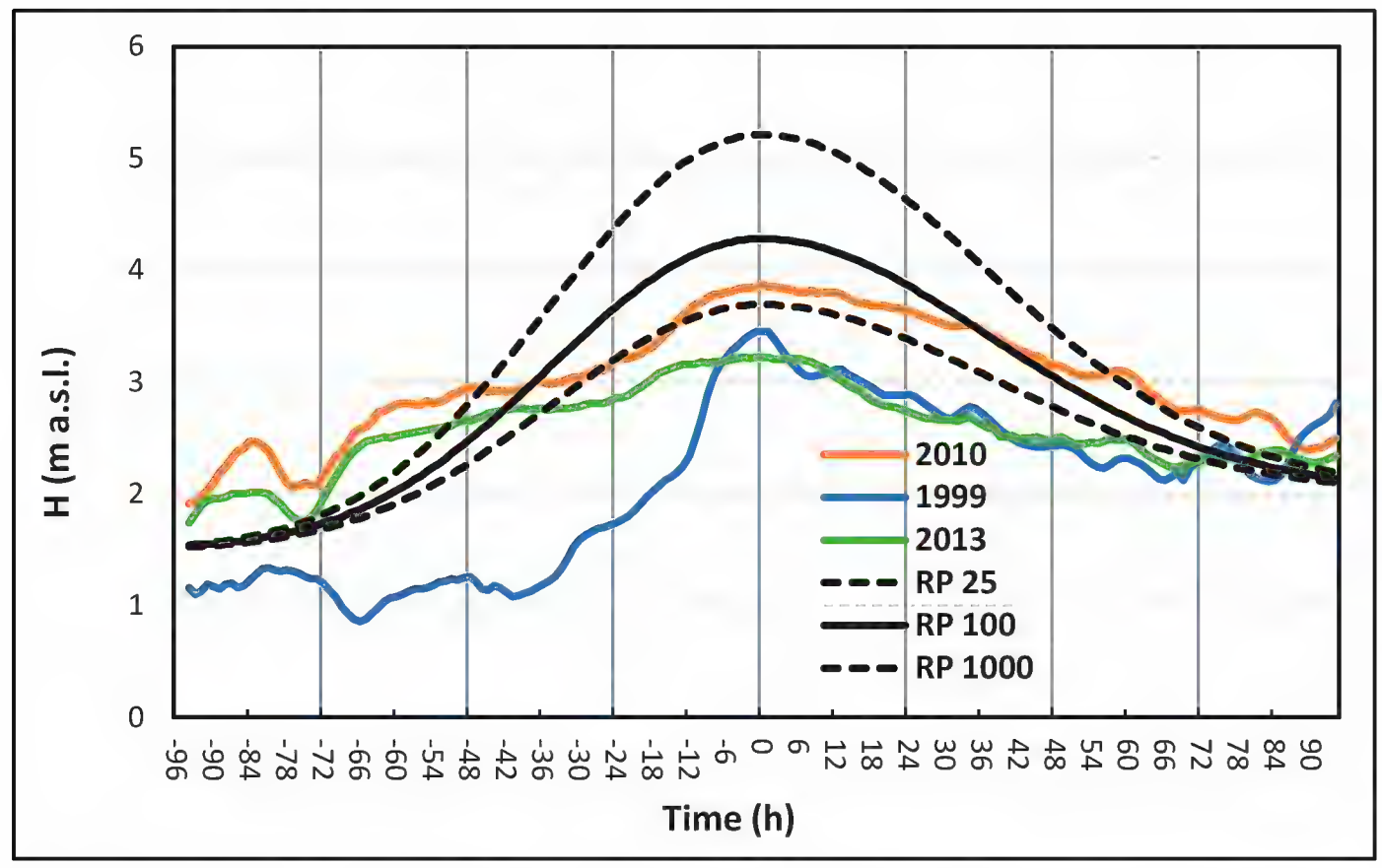

Figure 5. Recorded and synthetic water level charts in Metković.

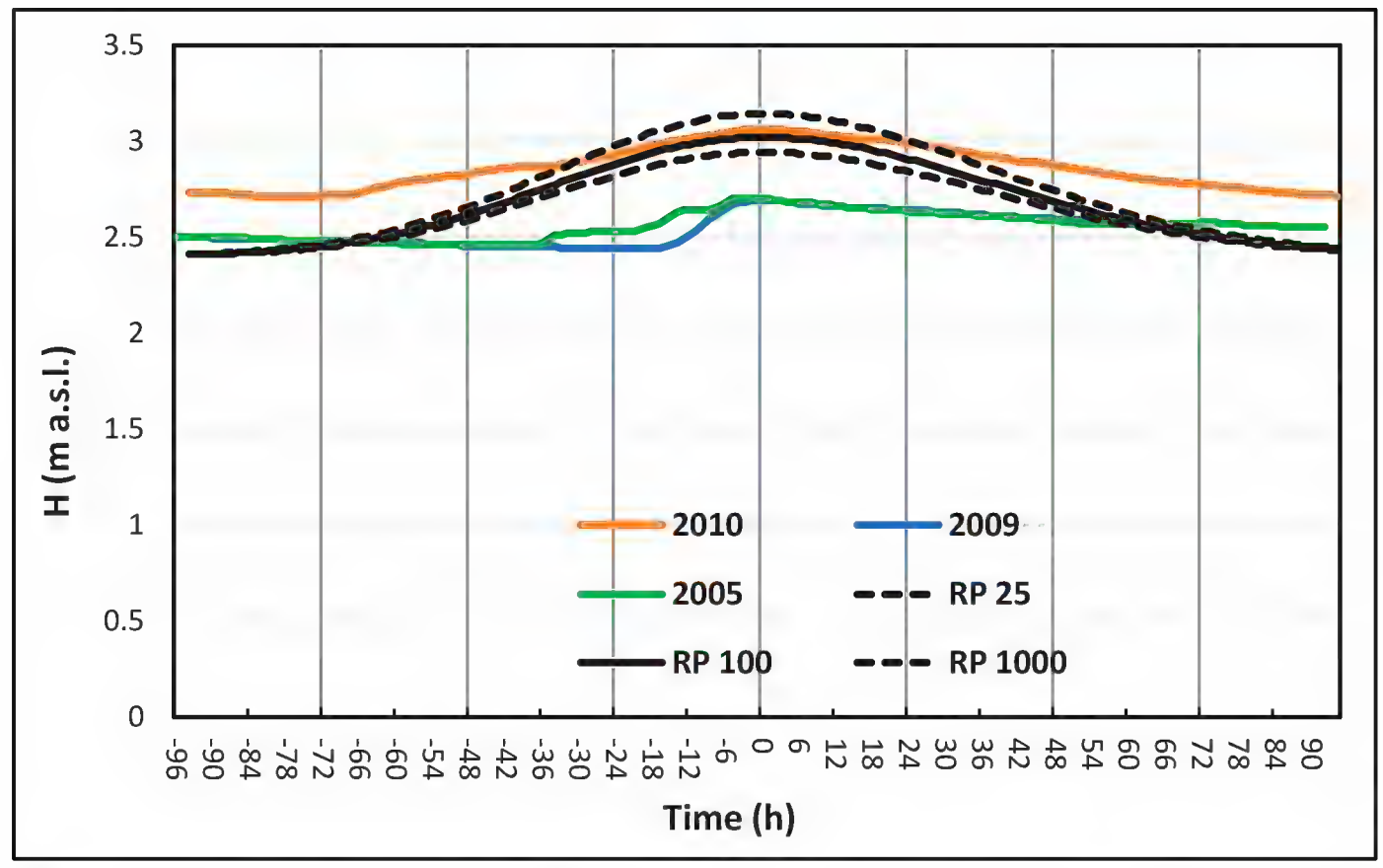

Figure 6. Recorded and synthetic water level charts of the Ustava Ušće Nizvodni (sea).

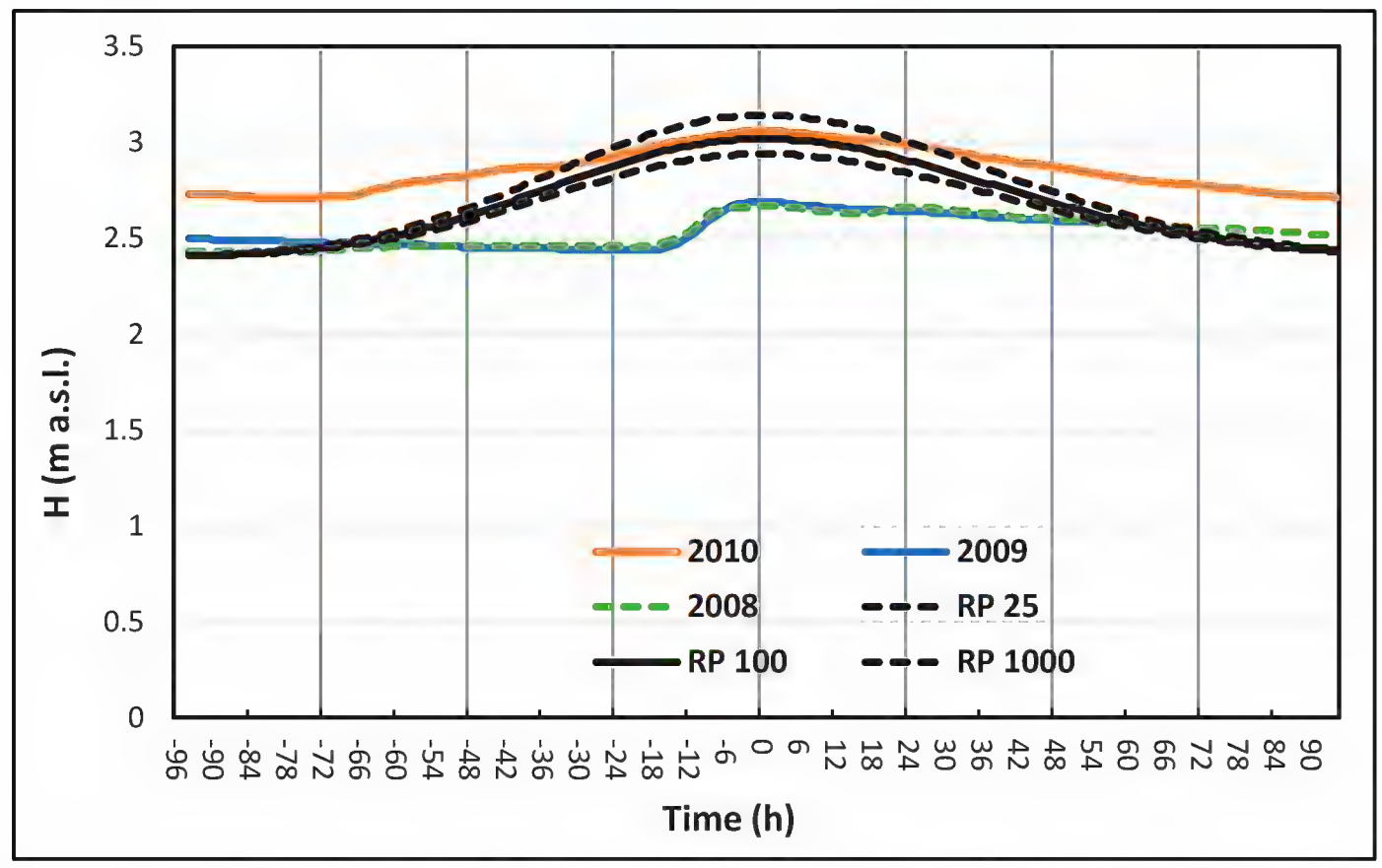

Figure 7. Recorded and synthetic level charts of Prud.

Hydraulic calculation and modelling

For the simulation of large waters, one-dimensional (1D) and 1D/two-dimensional (2D) hydrodynamic models of the Neretva River and its left and right banks from the border of the Republic of Croatia to the mouth of the Neretva River were created. MIKE by DHI program package was used, namely MIKE11 and MIKE FLOOD, which connect the 1D model created in MIKE11 and the 2D model created in MIKE21 (Fig. 8).

Model calibration and verification was carried out separately for four areas: Vid – Norin, Koševo – Vrbovci – Kuti, Opuzen – Ušće and Vidrice (Fig. 2), due to the complexity of the system and the duration of the calculation, for periods that include high water events (Table 8) (Kvesić et al. 2016). Registered water levels from hydrological stations located on the edges of the Neretva and

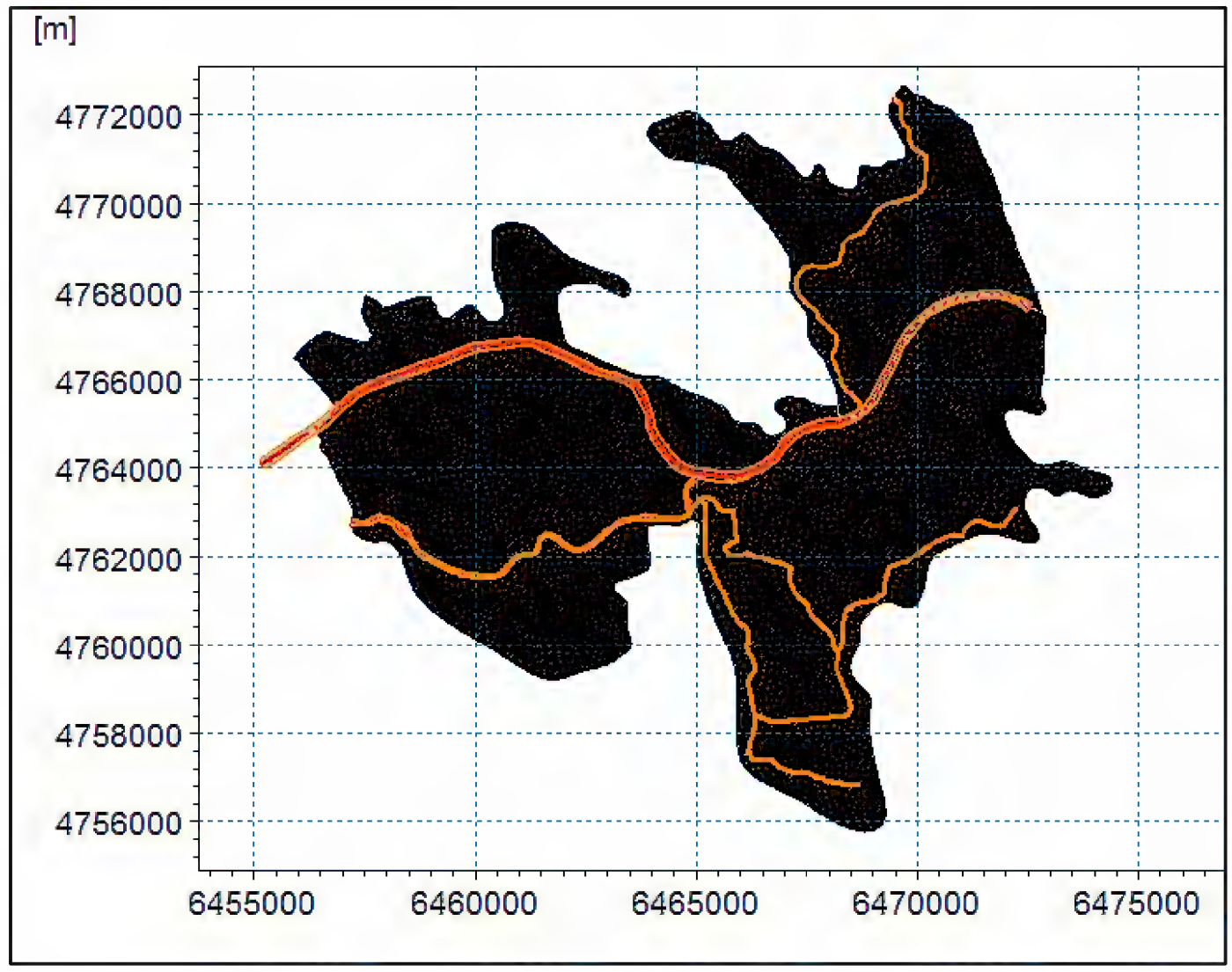

Figure 8. MIKE FLOOD 1D/2D model of the Donja Neretva (from the border of the Republic of Croatia to the mouth).

Table 8. Calibration and verification periods by areas.

Area	Calibration period	Verification period
Vid – Norin	Sep 15, 2010 – Feb 7, 2011	Sep 1, 2009 – Jun 30, 2010
Koševo – Vrbovci – Kuti	Aug 10, 2010 – Feb 10, 2011	Nov 1, 2011 – Jul 10, 2012.
Opuzen – Ušće		
Vidrice		

Mala Neretva River (Metković, Ustava Ušće) as well as on the edges of selected areas (Prud, Bijeli Vir, Kuti) were taken for boundary conditions. Hydrological stations located in the central part of the area (Kula Norinska, Kalebovac, Opuzen) were used as control points. Fig. 9 shows the boundary conditions for the Neretva River, which include water levels in Metković (upstream edge) and sea level change (downstream edge). The calibration was carried out for unsteady flow by changing the roughness coefficients for the main riverbed, lateral channels and inundation areas. The range of Manning coefficients was from 0.033 (riverbed) to 0.050 (inundation areas). The difference between modelled and measured water levels was mostly within an interval of ±5 cm. Higher water level differences were obtained only rarely in situations of relatively rapid water level changes (Kvesić et al. 2016). There can be several causes that lead to modelling inaccuracy. In inundation valley with numerous canals, such as the Neretva River delta, the geometry of the area plays important role for flow simulation. A digital terrain model and partially geodetic measurements were used in this study. More precise topographic input data will enable more accurate model calibration. Therefore, higher differences between modelled and measured water levels in the Neretva delta can be attributed to insufficiently

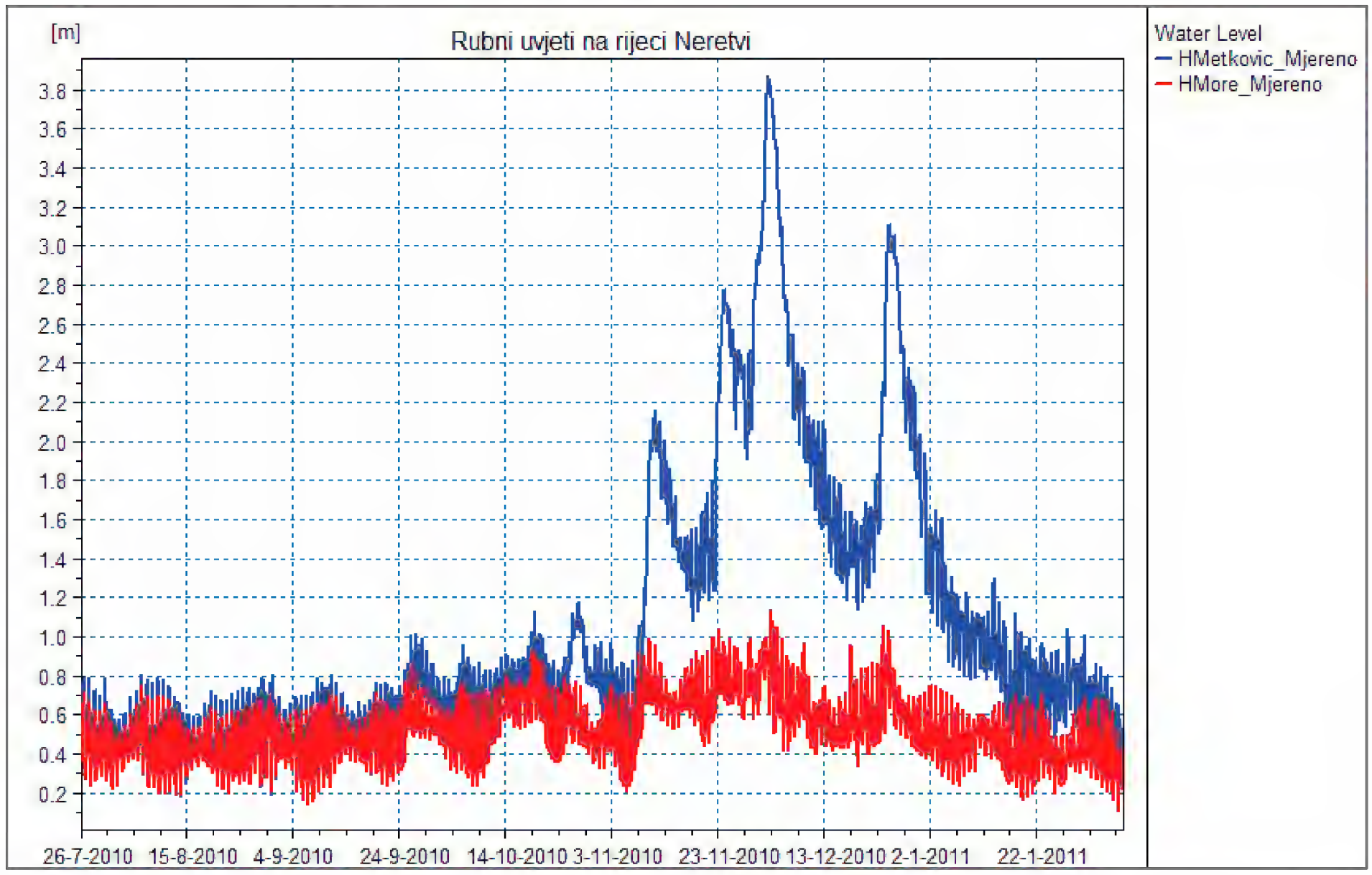

Figure 9. Boundary condition for the Neretva River (Metković: blue line; Sea: red line; Period: July 26, 2010 to January 31, 2011).

precise geometry. The cause of model inaccuracies can also be the influence of marginal karst sources. Their generosity is not negligible during rainy episodes. However, it is a series of sources of variable inflows, which were not considered as boundary inflows. However, they were indirectly involved in the calibration process through the measured water levels at nearby hydrological stations. Figs 10, 11 show the model calibration results for the Opuzen station (Neretva) and Opuzen Ustava (Mala Neretva), respectively. The established model can be considered acceptable considering the achieved results as well as the size and complexity of the entire system.

Pramanik et al. (2009) used MIKE FLOOD model to simulate flood inundation extent and flooding depth in the delta region of Mahanadi River basin in India. The model is calibrated for the year 2001 by comparing the maximum flood inundation extent simulated by the model with the corresponding actual inundated area obtained from remote sensing data. The calibration was carried out by changing the Manning's roughness coefficient of the flood plain. The validation was made for the year 2003 by comparing model results with flood reports prepared by State Water Resources Department (SWRD).

Masoero et al. (2013) modelled the 1951 flood event in the Po River delta (Italy), using a decoupled hybrid approach to the hydraulic modelling. The 1D model (HEC-RAC) is used to simulate the flow into the river and to compute the flow through the levee breach. This result is then adopted as the inflow condition for a 2D model (SOBEK) application on the inundated area. The roughness coefficient was used as a calibration parameter. The model calibration was performed in a steady-state mode, comparing results for different Manning coefficients with the historical records of discharges and water levels. Considering

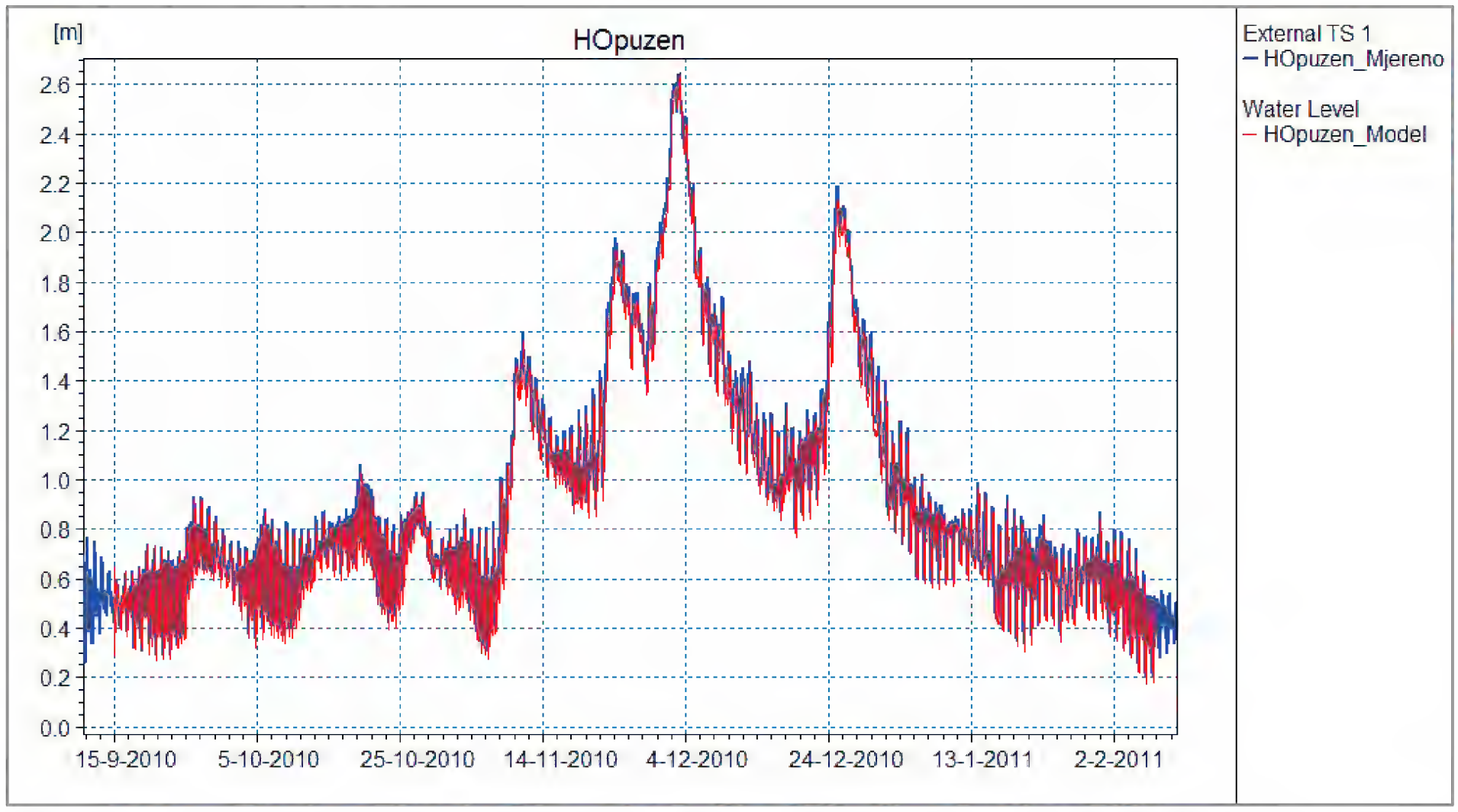

Figure 10. Measured (blue line) and modelled (red line) water levels for Opuzen (Period: September 15, 2010 to February 7, 2011).

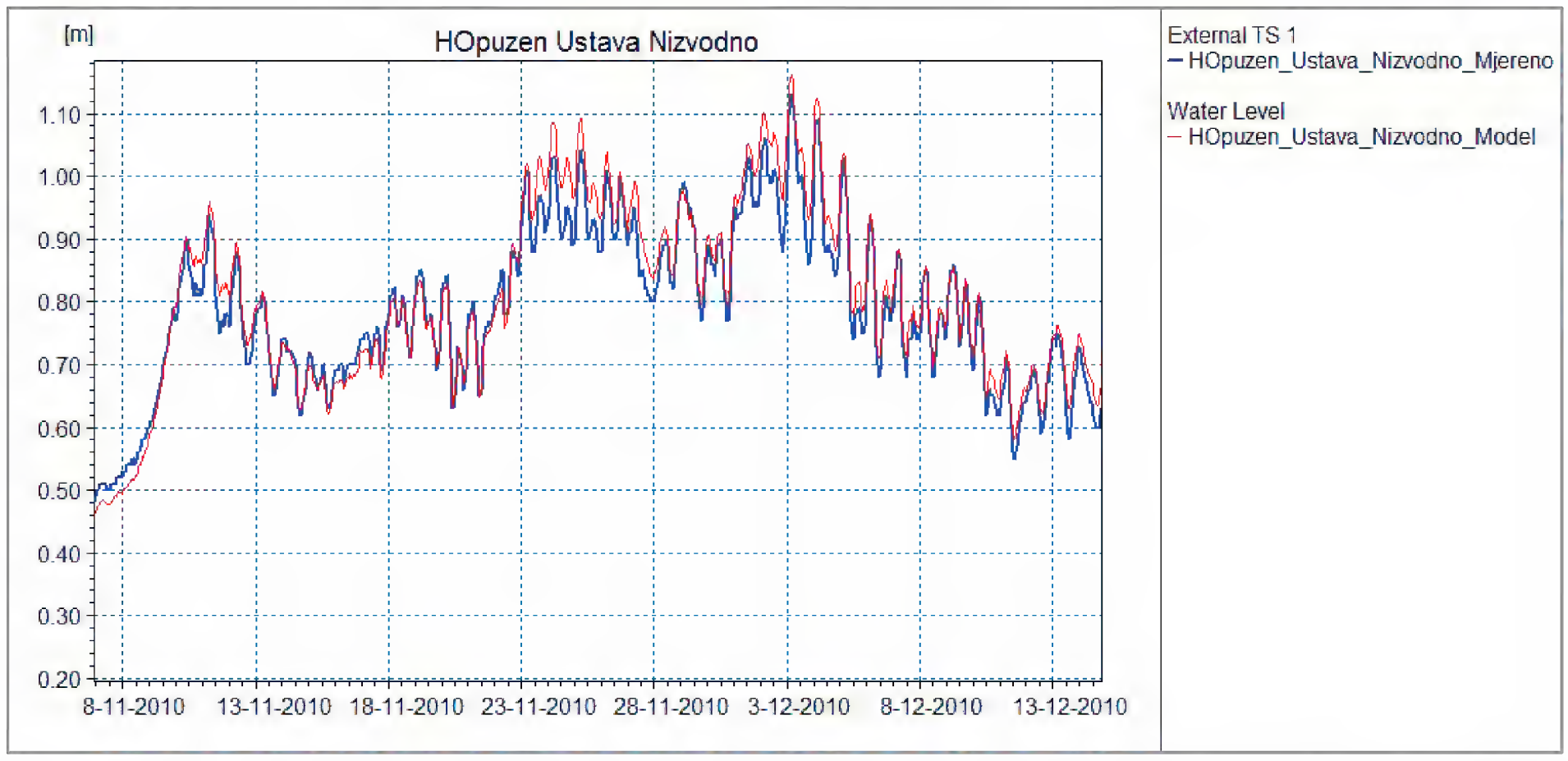

Figure 11. Measured (blue line) and modelled (red line) water levels for Opuzen Ustava Nizv. (Period: November 8, 2010 to December 13, 2010).

also the uncertainty associated to direct measurements, confidence interval of Manning coefficients was from 0.029 to 0.031.

Flows are not measured at the Metković station, as well as at the other hydrological stations in the territory of the Republic of Croatia, due to the influence of tides. Therefore, synthetic water level charts were defined at stations Metković (Fig. 5), Ustava Ušće nizv. (sea) (Fig. 6), and Prud (Fig. 7), for simulation of theoretical flood waves and their space distribution. The synthetic

water level chart for Metković is the upstream boundary condition of the model on the Neretva River. The synthetic water level chart for Ustava Ušće is the downstream boundary condition of the model on the Neretva and Mala Neretva rivers. The synthetic water level chart for Prud is the upstream boundary condition on the Norin River, the right tributary of the Neretva.

Results and discussion

Flooded areas

To identify flood risks and mitigate these risks in the Donja Neretva area, simulations of theoretical water waves for return periods of 5, 10, 25, 50, 100, 200, 500, and 1000 years were performed using calibrated and verified model. Fig. 12 shows the extent of flooding for three levels of probability and the current state of the flood protection system: high probability (dark blue) corresponds to 25-year high water, medium probability corresponds to 100-year high water, and low probability (light blue) corresponds to 1000-year high water. The corresponding flooded areas are 51 km^2 (high probability), 62 km^2 (medium probability) and 110 km^2 (low probability) (Fig. 12).

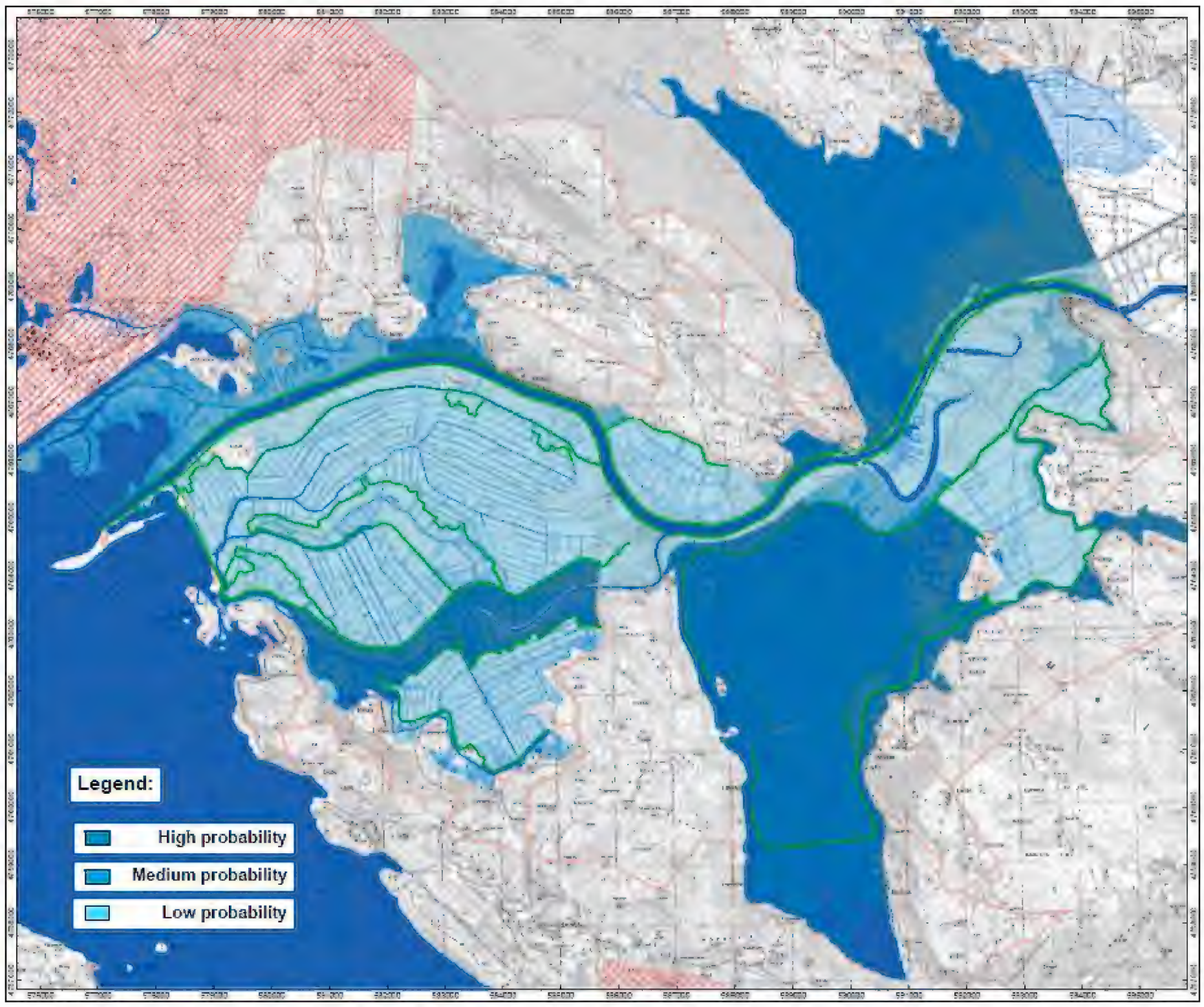

Figure 12. Flood distribution map in the Donja Neretva area for low, medium and high probability of occurrence.

The part of the Donja Neretva most at risk of flooding is the Vid – Norin area (Fig. 12), where the city of Metković has significantly expanded. Therefore, many residential, economic and infrastructure facilities are at risk. The mouth of the Norin is a particularly sensitive location which allows the Neretva flood waters to enter the Vid – Norin area. The Kuti area also has a high probability of flooding, although this risk is moderate because it does not have a high population density. It is a swampy area intersected by numerous small and large canals. This area is influenced by numerous karst springs located along the edge of the valley, which are fed by underground inflows from the karst hinterland. These inflows are difficult to quantify. They are not considered as a boundary condition in this study. However, by calibrating the model, they are also included in the calculation indirectly through the registered water levels. Furthermore, the area immediately next to the Mala Neretva riverbed had a high risk of flooding. It is a zone that is potentially directly threatened by the high waters of the Mala Neretva.

The area of Vrbovci and the area along the right bank of the Neretva (the settlements of Komin – Rogotin – Ploče) have a medium risk of flooding (Fig. 12). This is an area that is well protected by the existing embankments of the Neretva River.

The Opuzen-Ušće area has the lowest risk of flooding. This area is predominantly land reclamation and includes land reclamation cassettes Opuzen-Ušće, Vidrice, and Luka. Numerous flood defense embankments that follow the course of the Neretva and Mala Neretva Rivers have been built in this area.

Based on the runoff simulations, in addition to the scope of the flood itself, maps of the depth and speed of water in the flooded areas were defined for each return period. The depth maps represent the envelope of the maximum depths for the observed scenarios, and the depths were classified into intervals < 0.5, 0.5–1.0, 1.0–1.5, 1.5–2.0, 2.0–2.5, and > 2.5 m. The velocity maps represent the envelope of the maximum velocities for the observed scenarios, and the speeds were classified into intervals of < 0.5, 0.5–2.0, and > 2.0 m/s.

Deltas are exposed to the risk of flooding caused by the interaction of several potential triggers, such as high astronomical tides, storm surges, waves and large fluvial flows, which have also been established in Mediterranean deltas. Floods in the Neretva Delta are primarily caused by the surface inflow of fresh water from the upstream part of the basin. A smaller contribution to floods was provided by underground flow that appears in delta via numerous karst springs on the edge of the valley and then the action of the sea.

In comparison with other Mediterranean deltas, the key factors regulating the onset of flood events in the Evros River delta (Greece) are the prevailing weather conditions, along with rainfall levels (exceeding 10 mm/day) and the consequent rise of the sea level (above 0.2 m) attributed to southerly winds (Poulos et al. 2022). The Evros River discharge is recognized as a secondary factor acting mainly toward the persistence of the events and subsequent riparian flooding. In many deltas in the Mediterranean, sea level rise is recognised as a major potential cause of flooding (Sayol and Marcos 2018; Falciano et al. 2023).

Damages

After determining the flooded area, the damage was calculated separately for each return period. Damage to a flooded area can be calculated depending on several flood parameters such as: surface, depth, duration, flow rate, time of

appearance, pollution, and salinity (Messner et al. 2007; Kranen 2010; Solin and Skubinčan 2013; Kvesić et al. 2024).

Seven categories were adopted to calculate the damage: populated areas, economic areas, agricultural areas, permanent plantations, green areas, water management facilities, and potential human victims. Fig. 13 shows the amount of calculated damage from floods in the Donja Neretva area for the current situation, depending on the return period of high water. In the case of very large waters (return period of 1,000 years), the total damage amounted to 250 million Euros. By reducing the return period, the coverage of floods and other parameters used in the calculation of damage (e.g., water depth and duration) are reduced, thus reducing the amount of damage. For example, in the case of a 100-year flood (average probability of flooding), the total damage was 93 million Euros. Looking at the aforementioned categories, the greatest damage would occur in populated areas, the share of which would be greater than 90% of the total damage.

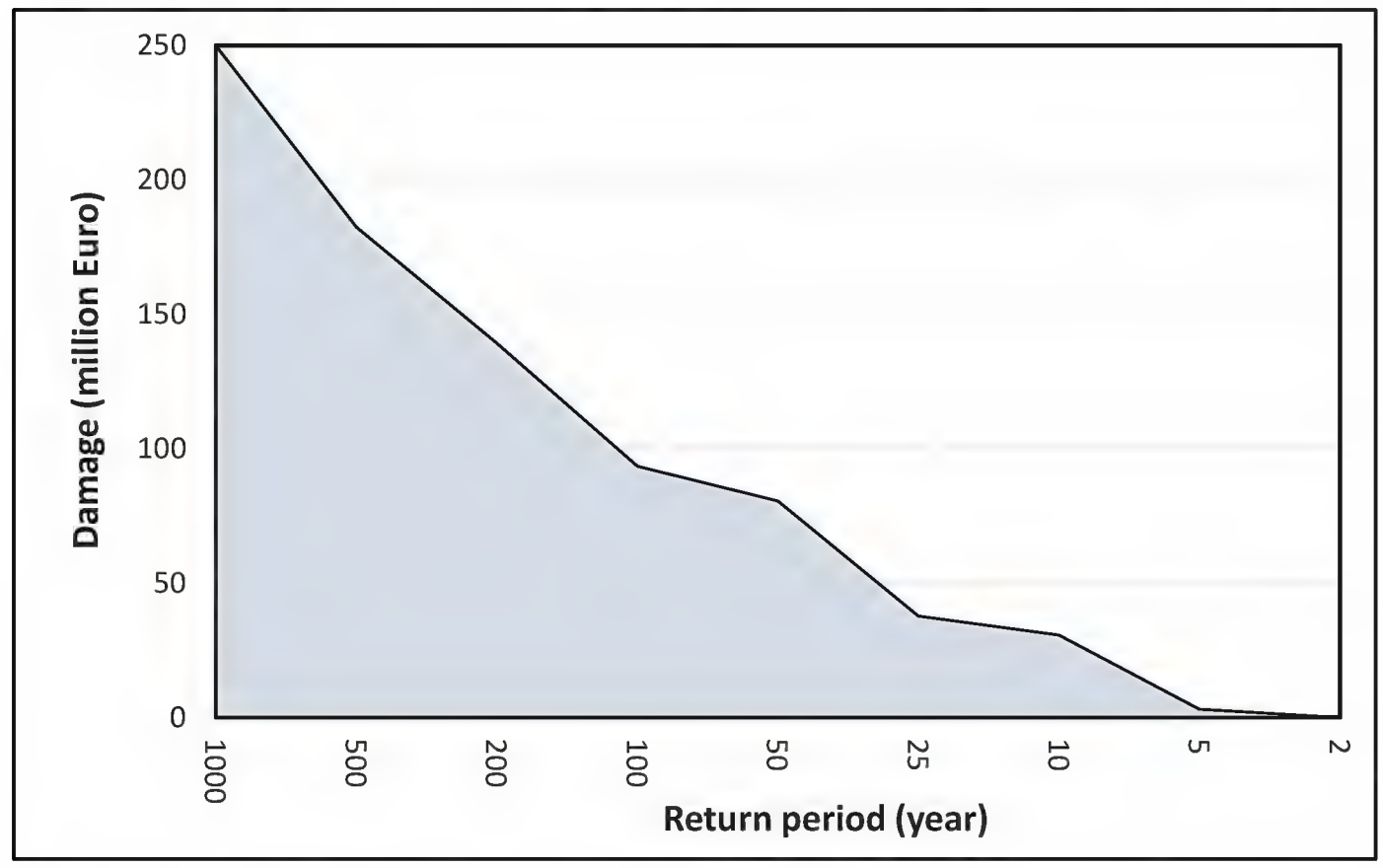

Figure 13. Flood damage in the Donja Neretva area.

Territorially, the greatest damages in the Donja Neretva area would occur in the wider area of the town of Metković, on both banks. This is the area of Vid – Norin on the right bank of the Neretva, then the area along the river itself (the town of Metković) and part of the valley south of the town (the area of Vrbovci – Koševo).

According to the "Flood Risk Management Plan" for the Republic of Croatia, the total potential flood damage for the entire country amounts to 22,600 million Euros, of which 4,258 million Euros refers to the basins of the Adriatic Sea. Consequently, the damage estimated for the Donja Neretva is approximately 1% and 6% of the total damage for the entire Republic of Croatia and Adriatic area, respectively.

Risk

Flood risk (R) is defined as the product of the probability of a flood event (P) and the potential adverse consequences (C) for human health, the environment and economic activities owing to such a flood event, based on the following formulas:

$$R = P \cdot C \quad (1)$$

$$C = \sum V \cdot S \cdot E \quad (2)$$

where V is vulnerability, S is susceptibility and E is exposure.

Vulnerability represents the value of a certain type of material asset in the considered element, expressed in monetary term. Sensitivity is expressed as a damage factor and depends on the flood parameters; its value ranges from 0 to 1. Exposure represents the probability that an inhabitant or material asset is exposed to a flood event and, its value ranges from 0 to 1.

Fig. 14 shows the risk of flooding for the population, that is, the potential number of victims of flood events with return periods of 5–1,000 years. The average number of potential human victims is 0.67 per year.

The monetized direct average annual damages were calculated separately for several different categories (populated areas, areas with economic use, agricultural areas, areas under permanent plantations, and green areas) (Table 9).

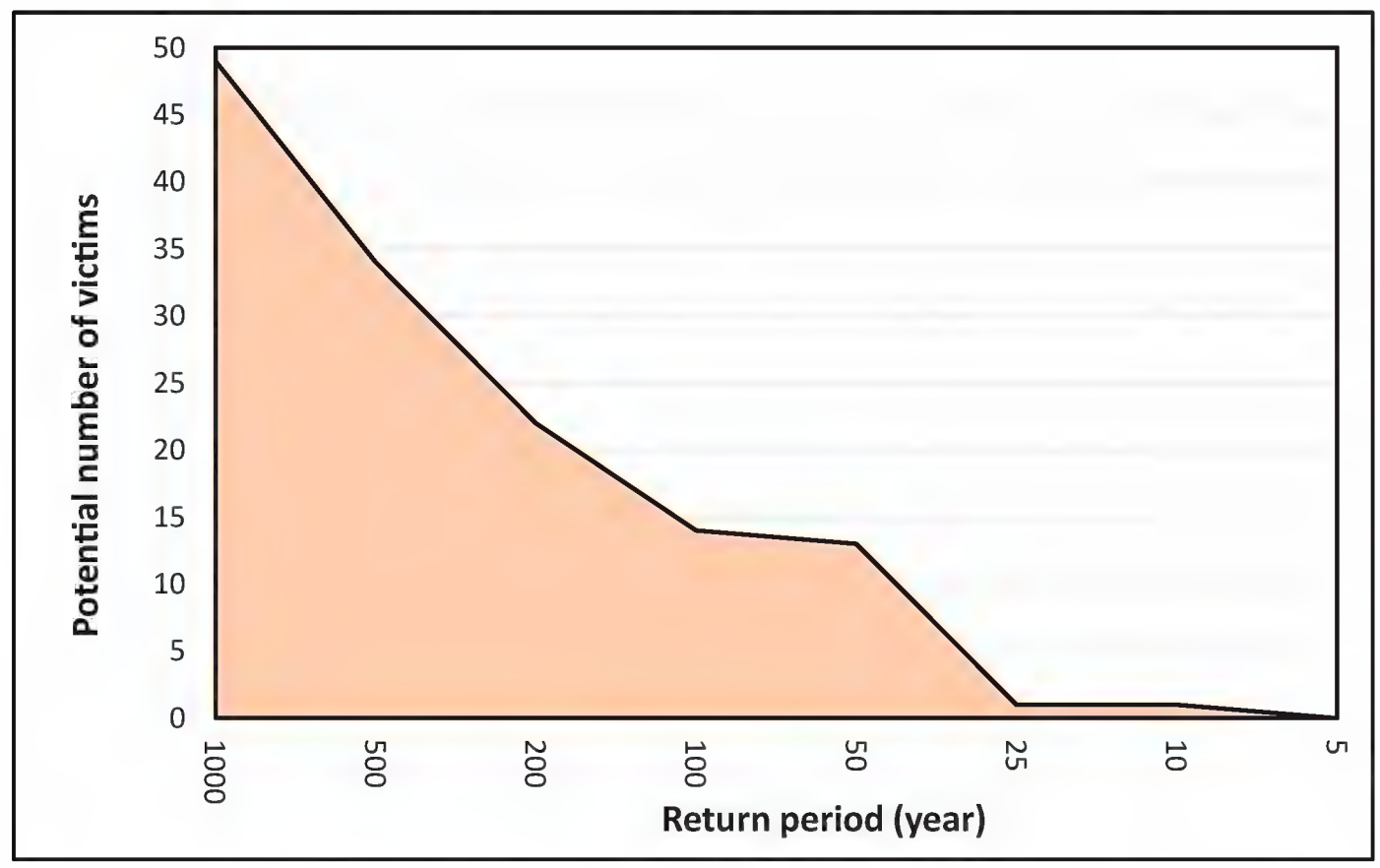

Figure 14. Number of potential human victims in the Donja Neretva area.

Table 9. Average annual damages for the current situation (year 2015) based on the considered categories.

Category	Average annual damage (Million €)
Populated area	11.47
Economic purpose	0.07
Agricultural area	0.07
Permanent plantations	0.03
Green area	0.00
Total	11.63

The total average annual damage (flood risk) in the Donja Neretva area for the condition defined in 2015 (before the construction of the Jerkovac embankment in Metković) amounts to 11.63 million Euros. If the impact of climate change is considered, the average number of potential human victims would be 0.88 per

year, and the total potential average damage would be 16.5 million Euros. It is an increase of 31% and 41%, compared to the condition defined in 2015.

Climate change simulation was made for sea level rise (downstream boundary condition) and increase in inflow, i.e. water level in Metković (upstream boundary condition). Assumed sea level rise is given in the Table 10, for three periods in the future. The greatest increase in the mean sea level of 87 cm (61%) was predicted for the end of the 21st century and the return period of 1,000 years. The corresponding upstream boundary condition had discharge increase of 23% (year 2100, return period 1,000). The flows of large waters in Metković were determined as a result of the simulation, because they are not normally estimated through the water level due to the influence of the sea. In such conditions, flood risks record an increase of 31% and 41% for the potential of human casualties and damage, respectively. This simulation also shows influence of the boundary conditions on the risk assessment in the delta area. The simulation is done to change both boundary conditions. In further research, the impact of each boundary condition could be analyzed separately.

Table 10. Assumed sea level rise (%) due to climate change at hydrological station Ustava Ušće Nizv.

Return period (year)	Average water level (m a.s.l.)	Year		
		2040	2070	2100
25	1.2	13%	29%	42%
100	1.3	21%	38%	53%
1000	1.43	29%	45%	61%

Analyzing variant solutions that would reduce the risks of flooding in the area of Donja Neretva, and after multi-criteria analysis, the optimal solution was chosen, which consists of the following measures:

- Construction of an embankment on the right bank of the Neretva near Metković, on the territory of the Republic of Croatia and Bosnia and Herzegovina, which has since been completed;
- Construction of a concrete defensive wall in combination with a mobile barrier on the right bank in the town of Metković;
- Construction of an embankment on Mislina with a defense height of 1,000–year water;
- Construction of an embankment near the settlement of Krvavac to protect against 50-year high water;
- Rehabilitation of the Neretva riverbanks in critical sections of shorter lengths;
- Construction of a self-regulating gate at the junction of the Norin and the Neretva rivers as a measure to reduce the height of flood water in the Neretva.

By implementing these measures, the average potential number of human victims could be reduced to 0.2 per year (reduction of 70%). With optimal measures, the average annual damage could be reduced to 2 million Euros, which is approximately six times less that of the current state (reduction of 83%). From the cost-benefit analysis, the optimal solution shows a positive result, and the benefit-cost ratio is 18.04.

Conclusions

The Neretva River is the largest river on the eastern coast of the Adriatic Sea with its inflow and basin. The river delta formed in the geological past over an area of approximately 190 km^2. Natural geomorphological and hydrological processes occurred mostly undistributed until the end of the 19th century when the first regulatory work in the region began. The current hydrological regime is strongly influenced by reservoirs and hydroelectric power plants built in the middle and upper upstream areas of the Neretva River, in the territories of Bosnia and Herzegovina. The plan is to build new hydropower plants in the Neretva and Trebišnjica basins, further impacting the hydrological regime.

Flood situations in the Neretva Delta are primarily caused by the inflow of large amounts of water from the upstream part of the basin (BiH). A smaller contribution to large waters was provided by numerous springs on the edge of the valley and the action of the sea. Precipitation that falls directly into the Donja Neretva area has the least impact on floods.

To quantify of flood events, a hydrological analysis of the available measurements and flood simulations were conducted. Owing to the influence of the sea, hydrological measurements in the delta area are focused on water level measurements, where there is no unambiguous relationship between water level and flow. Synthetic water waves were determined for return periods of 5–1,000 years. The MIKE FLOOD hydrodynamic model determined the coverage of floods for the specified return period, as well as the relevant flood parameters that were used to calculate damage and flood risk.

For the Donja Neretva area (Republic of Croatia), the potential material damage of approximately 250 million Euros and the possible number of human victims were determined for the existing conditions and different return periods. The estimated possible damage in the Neretva River delta amounts to 1% of the total flood damage for the Republic of Croatia. Flood risk was classified into three probability categories: high (return period of 25 years), medium (100-year flood), and low (1,000-year flood), with an average annual damage of 11.63 million Euros.

The present flood defense system of Donja Neretva includes numerous hydrotechnical structures (protective dikes, levees, canal networks, pumping stations, etc.). The level of flood protection has significantly increased in the last 50 years. Floods are natural phenomena that cannot be completely prevented; however, with the constant development of flood defense systems and the construction of protective and regulatory water structures, as well as the implementation of flood defense measures and other appropriate measures, flood risks can be reduced to an acceptable level. With the implementation of the proposed measures the average annual potential number of victims and the average material damage would be reduced by 70% and 83%, respectively.

Part of the conducted research was related to modelling the impact of climate change, which included sea level rise and increased water inflow from the upstream part of the basin. The estimated average annual number of victims was 0.88, and the potential annual damage was 16.5 million Euros, for the end of the 21st century, which represents an increase of 31 and 41%, respectively.

The flood simulation presented in this study was as part of the 2015 project (Kvesić et al. 2016). Hydrological series of up to 53 members were used, with

the last year being 2013. As part of further activities, the simulations could be repeated with extended series. In this way, climatic and hydrological variations from the last decade would also be considered.

In a large and complex system such as the Neretva delta, there is always a certain geometric (topographic) inaccuracy. Also, there is an influence of temporary and permanent springs along the edge of the valley without defined associated hydrographs. It is certainly reflected in the results of the simulations. However, such influences are partially compensated by the calibration process. In future activities, appropriate hydrological analyzes could be carried out with the aim of determining the hydrographs of marginal sources.

The analysis of flood events, the calculation of potential damages and risks, and the proposal of optimal measures for additional risk reduction represent a quality basis for the further development of flood protection and should help experts in making decisions related to flood defense. The aforementioned methodology is universal and can be applied to similar estuary and delta systems worldwide with their own specificities. Similarly, the occurrence of floods is important for numerous natural and ecological processes that occur in delta areas (estuaries). Therefore, the application and results of hydrodynamic modelling can also be used for ecological studies, as they quantify numerous hydrological parameters (e.g., water depth, flow rate, flood duration, and salinity). This is particularly important in the context of recommendations to preserve natural wetlands in the Mediterranean region, which includes this delta.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Funding

No funding was reported.

Author contributions

All authors have contributed equally.

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Data availability

All of the data that support the findings of this study are available in the main text.

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